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FOR

IN-SITU MIRROR CHARACTERIZATION

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TITLE: IN-SITU MIRROR CHARACTERIZATION

CROSS REFERENCE TO RELATED APPLICATION

This application claims priority from United States Provisional Patent Application No. 60/205,980 filed on May 19, 2000 and United States Provisional Patent Application No. 60/212,405 filed on June 19, 2000, the contents of which are incorporated herein by reference in their entirety.

BACKGROUND OF THE INVENTION

This invention in general relates to interferometry and in particular to interferometric apparatus and methods by which the local surface characteristics of photolithographic stage mirrors or the like may be interferometrically measured in-situ to provide correction signals for enhanced distance measurement accuracy.

Interferometry is a well established metrology used extensively in microfabrication processes to measure and control a host of critical dimensions. It is especially important in manufacturing semiconductors and the like where requirements for precision are **10** to **40**% better than critical dimensions of 0.1 μm or less.

Integrated circuits made of semiconductor materials are constructed by successively depositing and patterning layers of different materials on a silicon wafer while it typically resides in a flat exposure plane having Cartesian x-y coordinates to which there is a normal z-direction. The patterning process consists of a combination of exposure and development of photoresist followed by etching and doping of the underlying layers followed by the deposition of subsequent layers. This process results in a complex and, on the scale of microns, very nonhomogeneous material structure on the wafer surface.

Typically each wafer contains multiple copies of the same pattern called "fields" arrayed on the wafer in a nominally rectilinear distribution known as the "grid." Often, but not always, each field corresponds to a single "chip."

The exposure process consists of projecting the image of the next layer pattern onto (and into) the photoresist that has been spun onto the wafer. For an integrated circuit to function properly each successive projected image must be accurately matched to the patterns already on the wafer. The process of

determining the position, orientation, and distortion of the patterns already on the wafer, and then placing them in the correct relation to the projected image, is termed "alignment." The actual outcome, i.e., how accurately each successive patterned layer is matched to the previous layers, is termed "overlay."

In general, the alignment process requires both translational and rotational positioning of the wafer and/or the projected image as well as some distortion of the image to match the actual shape of the patterns already present. The fact that the wafer and the image need to be positioned correctly to get one pattern on top of the other is obvious. Actual distortion of the image is often needed as well. Other effects, such as thermal and vibration, may require compensation as well.

The net consequence of all this is that the shape of the first-level pattern printed on the wafer is not ideal and all subsequent patterns must, to the extent possible, be adjusted to fit the overall shape of the first-level printed pattern. Different exposure tools have different capabilities to account for these effects, but, in general, the distortions or shape variations that can be accounted for include x and y magnification and skew. These distortions, when combined with translation and rotation, make up the complete set of linear transformations in the plane.

Since the problem is to successively match the projected image to the patterns already on the wafer, and not simply to position the wafer itself, the exposure tool must effectively be able to detect or infer the relative position, orientation, and distortion of both the wafer patterns themselves and the projected image.

It is difficult to directly sense circuit patterns themselves, and therefore, alignment is accomplished by adding fiducial marks or "alignment marks" to the circuit patterns. These alignment marks can be used to determine the reticle position, orientation, and distortion and/or the projected image position, orientation, and distortion. They can also be printed on the wafer along with the circuit pattern and hence can be used to determine the wafer pattern position, orientation, and distortion. Alignment marks generally consist of one or more clear or opaque lines on the reticle, which then become "trenches" or "mesas" when printed on the wafer. But more complex structures such as gratings, which are simply periodic arrays of trenches and/or mesas, and checkerboard patterns

are also used. Alignment marks are usually located either along the edges of "kerf' of each field or a few "master marks" are distributed across the wafer. Although alignment marks are necessary, they are not part of the chip circuitry and therefore, from the chip maker's point of view, they waste valuable wafer area or "real estate." This drives alignment marks to be as small as possible, and they are often less than a few hundred micrometers on a side.

Alignment sensors are incorporated into the exposure tool to "see" alignment marks. Generally there are separate sensors for the wafer, the reticle, and/or the projected image itself. Depending on the overall alignment strategy, these sensors may be entirety separate systems or they may be effectively combined into a single sensor. For example, a sensor that can see the projected image directly would nominally be "blind" with respect to wafer marks and hence a separate wafer sensor is required. But a sensor that "looks" at the wafer through the reticle alignment marks themselves is essentially performing reticle and wafer alignment simultaneously and hence no separate reticle sensor is necessary. Note that in this case the positions of the alignment marks in the projected image are being inferred from the positions of the reticle alignment marks and a careful calibration of reticle to image positions must have been performed before the alignment step.

Furthermore, as implied above, essentially all exposure tools use sensors that detect the wafer alignment marks optically. That is, the sensors project light at one or more wavelengths onto the wafer and detect the scattering/diffraction from the alignment marks as a function of position in the wafer plane. Many types of alignment sensors are in common use and their optical configurations cover the full spectrum from simple microscopes to heterodyne grating interferometers. Also, since different sensor configurations operate better or worse on given wafer types, most exposure tools carry more than one sensor configuration to allow for good overlay on the widest possible range of wafer types.

The overall job of an alignment sensor is to determine the position of each of a given subset of all the alignment marks on a wafer in a coordinate system fixed with respect to the exposure tool. These position data are then used in either of two generic ways termed "global" and "field-by-field" to perform alignment. In global alignment the marks in only a few fields are located by the

alignment sensor(s) and the data are combined in a best-fit sense to determine the optimum alignment of all the fields on the wafer. In field-by-field alignment the data collected from a single field are used to align only that field. Global alignment is usually both faster, because not all the fields on the wafer are located, and less sensitive to noise, because it combines all the data together to find a best overall fit. But, since the results of the best fit are used in a feed-forward or dead reckoning approach, it does rely on the overall optomechanical stability of the exposure tool.

Alignment is generally implemented as a two-step process; that is, a fine alignment step with an accuracy of tens of nanometers follows an initial coarse alignment step with an accuracy of micrometers, and alignment requires positioning the wafer in all six degrees of freedom: three translation and three rotation. But adjusting the wafer so that it lies in the projected image plane, i.e., leveling and focusing the wafer, which involves one translational degree of freedom (motion along the optic axis, the z-axis or a parallel normal to the x-y wafer orientation) and two rotational degrees of freedom (orienting the plane of the wafer to be parallel to the projected image plane), is generally considered separate from alignment. Only in-plane translation (two degrees of freedom) and rotation about the projection optic axis (one degree of freedom) are commonly meant when referring to alignment. The reason for this separation in nomenclature is the difference in accuracy required. The accuracy required for in-plane translation and rotation generally needs to be on the order of several tens of nanometers or about 20 to 30% of the minimum feature size or critical dimension (CD) to be printed on the wafer. Current state-of-the-art CD values are on the order of several hundred nanometers, and thus, the required alignment accuracy is less than **100** nm. On the other hand, the accuracy required for out-of-plane translation and rotation is related to the total usable depth of focus of the exposure tool, which is generally close to the CD value. Thus, out-of-plane focusing and leveling the wafer require less accuracy than in-plane alignment. Also, the sensors for focusing and leveling are usually completely separate from the "alignment sensors" and focusing and leveling do not usually rely on patterns on the wafer. Only the wafer surface or its surrogate needs to be sensed. Nevertheless, this is still a substantial task requiring, among other things, precise knowledge about the vertical position (the altitude)

of the optical projection system above the wafer.

To achieve alignment, it is known to use dynamic interferometers in which distance measurements are enhanced through the use of dynamic elements whose angular orientation is controlled via feedback arrangements to assure that beams carrying distance information are properly aligned to provide optimal signal. Such interferometers are shown, for example, in International Application No. PCT/US00/12097 filed May 5, **2000**, and entitled "Interferometry Systems Having a Dynamic Beam-Steering Assembly For Measuring Angle and Distance " by Henry A. Hill. However, even with dynamic interferometers the shape of various reflecting elements impacts on the achievable accuracy in distance measurements and impacts on the achievable accuracy in angle measurements, because for the latter local slope changes influence beam directions, as stage mirrors undergo their various motions. Typically, the shape of such reflecting elements, such as thin high aspect ratio mirrors, is characterized off-stage and, if judged to be of adequate consistency, are then mounted on-stage. However, this is often unacceptable because the mounting process itself distorts the shape of the element compared with its inspected shape, and this change in shape can introduce measurement errors.

Accordingly, it is a major object of the present invention to provide interferometric apparatus and methods by which the shapes of on-stage reflecting elements, such as thin high aspect ratio mirrors, may be measured in-situ, after mounting, to develop correction signals that compensate for errors in optical path lengths and in beam directions related to shapes of reflecting surfaces.

It is another object of the present invention to provide interferometric apparatus and methods by which the shapes of on-stage reflecting elements, such as thin high aspect ratio mirrors, may be measured in-situ, after mounting, to develop correction signals that compensate for errors in optical path lengths and in beam directions related to shapes of reflecting surfaces arranged in orthogonal planes.

It is yet another object of the present invention to exploit information generated from the operating properties of dynamic interferometers by which the shapes of on-stage reflecting elements, such as thin high aspect ratio mirrors, may be measured in-situ, after mounting, to develop correction signals that

compensate for errors in optical path lengths and in beam directions related to shapes of reflecting surfaces.

It is yet another object of the present invention to provide interferometric apparatus and methods by which the shapes of off-stage reflecting elements, such as thin high aspect ratio mirrors, may be measured in-situ, after mounting, to develop correction signals that compensate for errors in optical path lengths and in beam directions related to shapes of reflecting surfaces.

Other objects of the present invention will, in part, be obvious and will, in part, appear hereinafter when reading the following detailed description in conjunction with the drawings.

SUMMARY OF THE INVENTION

Interferometric apparatus and methods by which the local surface characteristics of photolithographic mirrors or the like may be interferometrically measured in-situ to provide correction signals for enhanced distance and angular measurement accuracy. Surface characterizations along one or multiple datum lines in one or more directions may be made by measuring the angular changes in beams reflected off the surfaces during scanning operations to determine local slope and then integrating the slope to arrive at surface topology. The mirrors may be mounted either on photolithographic stages or off the photolithographic stages on a reference frame. For the simplest case one dynamic beam-steering assembly or interferometer subsystem is employed for this purpose. For mirror characterization in two orthogonal directions, at least two dynamic beam-stearing assemblies are used. One produces a signal that contains information about the change in slope of the mirror surface along the datum line and orthogonal to it and the other produces a signal that contains information about the angular orientation of the stage on which the mirror is mounted. These two signals are combined to extract information about the slope of the mirror along its datum line and orthogonal to it. The slope is then integrated to obtain topography as a function of displacement. Single beam interferometers are preferred because they can measure pitch, yaw, and displacement with only a single beam to the mirror. Measurements can be made of a plurality of mirrors facing in mutually orthogonal directions by sequentially holding one or more fixed relative to their elongated surfaces while translating the third along its elongated dimension and

repeating the process. Alternatively, all mirrors can be moved together to obtain relative mirror topography. Three beam-stearing assemblies may be used to fully characterize three corresponding mutually orthogonal mirrors and beam-stearing or interferometer subsystems may be mounted on or off the translation stage.

Once the mirror's in-situ topography is established, it is stored in look-up-tables (LUTs), or the like, to provide real-time error correction signals to improve precision during normal operation.

BRIEF DESCRIPTION OF THE DRAWINGS

The structure, operation, and methodology of the invention, together with other objects and advantages thereof, may best be understood by reading the detailed description in connection with the drawings in which each part has an assigned numeral that identifies it wherever it appears in the various drawings and wherein:

Fig. 1 is a diagrammatic perspective view of an interferometric apparatus employing a pair of orthogonally arranged dynamic interferometers by which the shape of an on-stage mounted elongated object mirror may be characterized in situ along a datum line as the stage is translated in one direction;

Fig. 2 is a diagrammatic perspective view of an interferometric apparatus employing a pair of orthogonally arranged dynamic interferometers by which the shapes of on-stage orthogonally mounted elongated object mirrors may be characterized in situ along datum lines associated with each mirror as the stage is translated preferably first in one direction and then in an orthogonal direction or by which the relative shapes of the mirrors may be obtained by simultaneous motion of the stage along orthogonal directions;

Fig. 3 is a diagrammatic perspective view of an interferometric apparatus employing three orthogonally arranged dynamic interferometers by which the shapes of on-stage orthogonally mounted elongated object mirrors may be characterized in situ along multiple orthogonal datum lines associated with each mirror as the stage is translated along three orthogonal directions;

Figs. 4a and 4b are, respectively, diagrammatic top and an elevational views of an interferometer for use in the apparatus of **Fig. 3;**

Fig. 5 is a flow chart in accordance with a method of the invention; and

Fig. 6 is a diagrammatic perspective view of an interferometric apparatus employing three on-stage mounted orthogonally arranged dynamic interferometers by which the shapes of corresponding off-stage orthogonally mounted elongated object mirrors may be characterized in situ along multiple orthogonal datum lines associated with each mirror as the stage is translated along three orthogonal directions.

DETAILED DESCRIPTION

Reference is now made to **Fig. 1** which is a diagrammatic perspective view of an interferometric system **15** that employs a pair of orthogonally arranged dynamic interferometers or interferometer subsystems by which the shape of an on-stage mounted elongated object mirror may be characterized in situ along a datum line. As shown in **Fig. 1**, system **15** comprises a stage **16** that preferably forms part of a photolithographic apparatus for fabricating semiconductor products such as integrated circuits or chips. Affixed to stage **16** is a thin, high aspect ratio planar mirror **50** having a y-z reflective surface **51** elongated in the y-direction. Also, fixedly mounted to stage **16** is another thin, high aspect ratio planar mirror **60** having an x-z reflective surface **61** elongated in the x-direction. Mirrors **50** and **60** are mounted on stage **16** so that their reflective surfaces, **51** and **61**, respectively, are nominally orthogonal to one another. Stage **16** is otherwise mounted in a well-known manner for nominally plane translation but may experience small angular rotations about the x, y, and z axes due to bearing and drive mechanism tolerances. In normal operation, system **15** is adapted to be operated for displacement in only the y-direction.

Fixedly mounted off-stage is a single beam dynamic interferometer (or interferometer subsystem) **10** for measuring angular rotation of stage **16**, and thus planar mirror reflecting surface **51**, about the y and z axes as stage **16** translates in the y-direction. To accomplish this, dynamic interferometer **10** is structured and arranged in the manner described in aforementioned PCT Patent Application filed May 5, **2000** and entitled " Interferometry Systems Having a Dynamic Beam-Steering Assembly For Measuring Angle and Distance" by Henry A. Hill which is incorporated herein by reference in its entirety. As described in that application, mirrors are provided with beam steering capability by which bothersome stage rotations are measured to provide feedback signals that are used to maintain beams on paths that are normal to the mirrors. Here, the return beam component of beam **12** is monitored,

and its angle is measured via interferometric apparatus such as that described in U.S. Patent Application No. 60/**201**,**457** filed on May 3, 2000 in the name of Henry Allen Hill and entitled "Apparatus And Method(s) For Measuring And/Or Controlling Differential Paths Of Light Beams", the entirely of which is incorporated herein by reference.

Input beam **12** preferably comprises two orthogonally polarized components having a difference in frequencies f_1. A source of input beam **12** such as a laser can be any of a variety of frequency modulation apparatus and/or lasers. For example, the laser can be a gas laser, *e.g.*, a HeNe laser, stabilized in any of a variety of conventional techniques known to those skilled in the art, see for example, T. Baer *et al.*, "Frequency Stabilization of a 0.**633** μm He-Ne-longitudinal Zeeman Laser," *Applied Optics*, **19**, **3173**-**3177** (**1980**); Burgwald *et al.*, U.S. Pat. No. 3,**889**,**207**, issued June 10, **1975**; and Sandstrom *et al.*, U.S. Pat. No. 3,**662**,**279**, issued May 9, **197**2. Alternatively, the laser can be a diode laser frequency stabilized in one of a variety of conventional techniques known to those skilled in the art, see for example, T. Okoshi and K. Kikuchi, "Frequency Stabilization of Semiconductor Lasers for Heterodyne-type Optical Communication Systems," *Electronic Letters*, **16**, **179**-**181** (**198**0) and S. Yamaqguchi and M. Suzuki, "Simultaneous Stabilization of the Frequency and Power of an AlGaAs Semiconductor Laser by Use of the Optogalvanic Effect of Krypton," *IEEE J. Quantum Electronics*, **QE-19**, **1514**-**151**9 (**198**3).

Two optical frequencies may be produced by one of the following techniques: (1) use of a Zeeman split laser, see for example, Bagley *et al.*, U.S. Patent No. 3,**458**,**259**, issued July 29, **196**9; G. Bouwhuis, "Interferometrie Mit Gaslasers," Ned. T. Natuurk, **34**, **225**-**232** (Aug. **196**8); Bagley *et al.*, U.S. Patent No. 3,**656**,**853**, issued April 18, **1972**; and H. Matsumoto, "Recent interferometric measurements using stabilized lasers," *Precision Engineering*, **6**(2), 87-94 (**198**4); (2) use of a pair of acousto-optical Bragg cells, see for example, Y. Ohtsuka and K. Itoh, "Two-frequency Laser Interferometer for Small Displacement Measurements in a Low Frequency Range," *Applied Optics*, **18**(2), **219**-**224** (**197**9); N. Massie *et al.*, "Measuring Laser Flow Fields With a 64-Channel Heterodyne Interferometer," *Applied Optics*, **22**(14), **2141**-**215**1 (**198**3); Y. Ohtsuka and M. Tsubokawa, "Dynamic Two-frequency Interferometry for Small Displacement Measurements," *Optics and Laser Technology*, **16**, 25-29 (**1984**); H. Matsumoto, *ibid.*; P. Dirksen, *et al.*, U.S. Patent No. 5,**485**,**272**,

issued Jan. 16, 1996; N. A. Riza and M. M. K. Howlader, "Acousto-optic system for the generation and control of tunable low-frequency signals," *Opt. Eng.*, 35(4), 920-925 (1996); (3) use of a single acousto-optic Bragg cell, see for example, G. E. Sommargren, commonly owned U.S. Pat. No. 4,684,828, issued Aug. 4, 1987; G. E. Sommargren, commonly owned U.S. Pat. No. 4,687,958, issued Aug. 18, 1987; P. Dirksen, *et al.*, *ibid.*; (4) use of two longitudinal modes of a randomly polarized HeNe laser, see for example, J. B. Ferguson and R. H. Morris, "Single Mode Collapse in 6328 Å HeNe Lasers," *Applied Optics*, 17(18), 2924-2929 (1978); (5) use of birefringent elements or the like internal to the laser, see for example, V. Evtuhov and A. E. Siegman, "A "Twisted-Mode" Technique for Obtaining Axially Uniform Energy Density in a Laser Cavity," *Applied Optics*, 4(1), 142-143 (1965); or the use of the systems described in U.S. Pat. Application with Serial No. 09/061,928 filed 4/17/98 entitled "Apparatus to Transform Two Non-Parallel Propagating Optical Beam Components into Two Orthogonally Polarized Beam Components" by H. A. Hill, the contents of which are incorporated herein by reference.

The specific device used for the source of beam **12** will determine the diameter and divergence of beam **12**. For some sources, *e.g.*, a diode laser, it will likely be necessary to use conventional beam shaping optics, *e.g.*, a conventional microscope objective, to provide beam **12** with a suitable diameter and divergence for elements that follow. When the source is a HeNe laser, for example, beam-shaping optics may not be required.

Another dynamic interferometer **20,** preferably of the same design as that of interferometer **10**, is fixedly mounted off-stage to measure the angular rotation of stage **16** about the x and z axes. To achieve this, interferometer **20** projects a beam **22** on to mirror surface **61**. A return component of beam **22** is sent to an angle measuring interferometer as described above. Beam **22** is similarly generated as was beam **12**.

While system **15** is normally operated to measure y translation, it is operated in a special mirror characterization mode to measure the shape of mirror surface **51** in situ along a datum line thereof. In the mirror characterization mode, stage **16** is translated in the y-direction so that the input beam **12** scans the mirror surface **51** along a datum line and generates a signal containing information indicative of its angular orientation and surface departure in the x-direction and z-direction, along with any contributions due to variations in the translation mechanism for moving stage **16**.

Simultaneous with translation of stage **16** in the y-direction, interferometer **20** monitors a single point on mirror **61** corresponding to the intercept point of beam **22** with reflecting surface **61**. This step permits measurement of the rotation of stage **16** due to mechanical contributions of its translation mechanism, such as bearings, drive mechanisms, and the like. With this information, two signals are generated. The first from interferometer **10** which contains information about the change in slope of the mirror surface **51** along a datum line and orthogonal to the datum line, and the second from interferometer **20** which contains information about the angular orientation of stage **16**. These two signals are combined to extract information only about the slope of mirror **51** along its datum line and orthogonal to its datum line, *i.e.*, dx/dy and dx/dz. dx/dy is then integrated to obtain the x as a function of y. Thus, by measuring the direction of the change of the output beam **12** in the x-y and x-z planes and accounting for contributions to those changes brought about by changes in stage rotations, the shape of mirror surface **51** can be determined along a datum line and the slope dx/dz can be determined along the datum line while it is mounted in its working environment.

Single beam interferometers are preferred for this application because they can measure pitch ,yaw, and distance (P, Y, and D) with only a single beam going to the stage mirror **50**. Without changing the normal operation, one can extract in-situ information about mirror shape with no additional hardware changes.

However, the second measurement in a second direction is required because with translation in the y-direction, stage bearings and the like cause the stage to wobble introducing large errors in orientation. Therefore, use is made of mirror surface **61** to measure the deviation or change in orientation of the stage by looking at the return beam part of **22**, also done with a preferably dynamic interferometer.

An important feature of the use of single beam interferometers for this application is it contains all spatial frequencies up to the cutoff frequency given by $1/d$, where d is the beam diameter whereas use of a double beam interferometer, such as the HSPMI, would cause loss of all spatial frequencies that have wavelengths equal to the beam spacing of the two double beams or harmonics thereof so the shape could not be recovered.

It will evident to those skilled in the art that the second interferometer **20** could be another form of angle measuring interferometer including multiple beam

interferometers (not shown) but of the type shown and described in, for example, "Differential Interferometer Arrangements for Distance and Angle Measurements: Principles, Advantages, and Applications, C. Zanoni, VDI Berichte NR. 749, (1989), the contents of which are included herein by reference in its entirety, without departing from the scope or spirit of the present invention.

Reference is now made to Fig. **2** which is a diagrammatic perspective view of an interferometric apparatus depicted as system **115**. System **115** employs a pair of orthogonally arranged dynamic interferometers by which the shapes of on-stage orthogonally mounted elongated object mirrors may be characterized in situ along datum lines associated with each mirror as a stage is translated first in one direction and then in an orthogonal direction or by which the relative shapes of the mirrors may be obtained by simultaneous motion of the stage along orthogonal directions.

As seen in **Fig. 2**, system **115** comprises a stage, again **16**, mounted for plane translation but now normally operated to measure both x and y motion. A thin, high aspect ratio mirror **150** having a mirror surface **151** elongated in the y-direction is affixed to stage **16**, and a thin, high aspect ratio mirror **160** having an elongated reflecting surface **161**, elongated in the x-direction, is also fixedly mounted to stage **16** and nominally orthogonal to mirror **150**.

System **115** may also be operated in one of two mirror characterization modes to measure the surfaces **151** and **161** in situ. In a first mirror characterization mode, system **115** is operated in the manner of the mirror characterization mode of system **15** in **Fig. 1** to obtain the shape of surface **151**. Then, stage **16** is moved in the x-direction, holding the y-translation fixed to obtain the shape of mirror **161** in a manner analogous to that for obtaining the shape of mirror **151**. Thus, this is a two step operation.

In a second mirror characterization mode, stage **16** can be moved in x and y simultaneously. However, only the relationships between the shapes of mirror surfaces may be obtained. Only limited information would be obtained using this mode, but if this information is sufficiently for the intended downstream use, this mode eliminates one step in the previous process.

In connection with normal operation of both the embodiments of **Figs. 1 and 2** the goal is to obtain information about the shape of the mirrors so that this information can be used to correct for the influence of the mirror shapes on the precision with which distance can be measured. In this regard, a distance correction algorithm may

be used which can be implemented with a look up table (LUT) or polynomial or Fourier series closed form approximation to adjust distance measurements. Corrections of the order of 1/10 of a nanometer are possible.

Fig. 3 is a diagrammatic perspective view of an interferometric apparatus employing three orthogonally arranged dynamic interferometers by which the shapes of on-stage orthogonally mounted elongated object mirrors may be characterized in situ along multiple orthogonal datum lines (the x-z, x-y, and y-z planes) associated with each mirror as a stage is translated along three orthogonal directions, x, y, and z.

Referring now to **Fig. 3,** the apparatus of this embodiment is shown as a system **202** that comprises stage **16** atop of which is fixedly mounted a plane mirror **270** and a plane mirror **260**. Plane mirror **260** has a reflecting surface **261** oriented in the x-z plane and elongated in the x-direction. Plane mirror **270** has a reflecting surface **271** oriented in the y-z plane and elongated in the y-direction. Mirror **270** also has a top reflecting surface **272** oriented in the x-y plane and elongated in the y-direction.

Fixedly mounted in a reference body (not shown) is an elongated plane mirror **280** having a lower reflective surface facing downwardly, towards stage **16**. Fixedly mounted with respect to a portion of stage **16** making translations in only the x direction is a single beam interferometer **231** that is adapted to measure the vertical separation or altitude between mirror surface **272** and the underside of mirror **280**.

Single beam interferometer **210** having output and return beam components in beam **212** measures x and pitch and yaw about the y and z axes as before. Single beam interferometer **220** having output and return beam components in beam **222** measures y and pitch and yaw about the x and z axes, respectively, also as before.

At any altitude the x and y profiles of mirrors **272** and **260** may be measured using the procedures previously described. In addition to this, however, this embodiment permits the x and y shapes of mirrors **260** and **270** to also be measured at different altitudes. For example, the x and y shapes may be determined at one altitude of stage **16** and then at another that may be vertically displaced, say 4 to 5 mm, above or below the first. To do this, angular changes in stage **16** introduced by motion in the z-direction must be taken into account for optimal precision.

Interferometer **231** is adapted in a manner to be described to be sensitive to changes in orientation of the stage **16** by virtue of it being a single beam interferometer, which makes a single pass of surfaces **280** and **272**, and is otherwise

configured to measure pitch and yaw for beam **233**. Source/detector **230** feeds interferometer **231** (See Figs. 4a and 4b). Therefore, if stage **16** rotates about the x or y axis, during a translation in the z direction interferometer **231** corrects for that. If beam **233** rolls about the x-axis for beam **212** and rolls about the y axis for beam **222** correction is also present. With that information for movement in the z direction, rotation of the stage **16** can be determined with motion in z compensated for such that surfaces **271** and **261** can be mapped in the in z-direction as well as y and x directions.

It will also be evident to those skilled in the art that the shape of surface **272** can also be obtained in the process of determining the shapes of surfaces **261** and **271**.

Figs. 4a and 4b are, respectively, diagrammatic top and an elevational views of an interferometer **231** for use in the system **202** of **Fig. 3**. As seen there, interferometer **231** comprises a first polarizing beam splitter **300** (PBS) having a polarizing beam splitter layer **302** arranged perpendicular to the paper. PBS **300** is followed by a PBS **312** having PBS layer **324** oriented at right angles to PBS layer **302**. PBS **312** is followed by a quarter-wave plate **314** and then a Porro prism **316**.

PBS **300** has on one side a quarter-wave plate **304** atop of which sits a mirror reflecting surface **306**, and on the opposite side of PBS **300** is provided with a quarter-wave plate **308** on which sits a reflective surface **310**.

PBS **312** has a quarter-wave plate **326** on its top surface and another quarter-wave plate **330** on the bottom side. Mirrors **280** and **270** reside above and below quarter-wave plates **326** and **330**, respectively.

A third PBS **318** is provided at the output end of PBS **300** and includes a PBS layer **319**. The return component of beam **232** is split by PBS **318** into two beams **343** and **345** that are sent to photodetectors **322** and **320**, respectively, to be converted to electrical signals for further analysis.

With this arrangement, if interferometer **231** rotates it doesn't change the orientation of the output beam. However, if either mirror **270** or **280** rotate, the corresponding angles will be measured.

The top view of interferometer in **Fig. 4a** depicts the path which the reference beam experiences as it travels through the interferometer **231** and the elevational view of **Fig. 4b** depicts the path which the measurement beam experiences as it travels through interferometer **231**.

Having described apparatus by which a stage mirror may be characterized in situ, attention is now directed to **Fig. 5** which shows a flowchart for a method for characterizing stage mirror topography in situ. As seen there, the method is first started in block **400**, preferably with the stage **16** in a park position. The next step is to mount an elongated plane object mirror on a translation stage for plane motion as shown in block **402**. This is followed by the step of directing a single beam from an interferometer at the object mirror. Next, the stage is moved along the elongated direction of the mirror while the beam is directed at it so that the beam scans the mirror along a datum line as shown in block **406**. Following this, the return beam from the mirror is monitored and the change in angle of the return beam is measured while the mirror is scanned to generate a signal containing information about the local slope of the mirror surface along the datum line as shown in block **408**. Then, the stage angular orientation is measured by directing a single beam from another orthogonally positioned interferometer at a point on the stage that does not translate as the stage moves in the direction of the long dimension of the mirror as shown in block **410**. Following this, the signal from the first interferometer is combined with the measured stage orientation information to determine the local slope of the mirror surface as a function of stage displacement. Then in block **414**, the slope information is integrated to obtain the mirror topography along the datum line. Finally, the process may be repeated as shown in block **416** to map either another orthogonally positioned stage mirror or to perform scanning along datum lines on the same mirror displaced from initial datum lines in the z-direction.

It will be appreciated that the foregoing process may be implemented via a suitably programmed general purpose computer or via dedicated microprocessors that additionally may be used to exercise overall control of system hardware elements, provide a user interface for system control and human intervention, and perform general housekeeping functions.

Having described the various embodiments, it will be obvious to those skilled in the relevant art how to make additional changes based on the teachings of the invention and all such changes are intended to be within the scope of the invention. For example, It is known in the metrology of lithography tool wafer stages to also place an interferometer on the wafer stage and place an associated bar mirror off the wafer stage on a reference frame of the lithography tool. See, for example, commonly owned U.S. Patent No. 5,724,136 entitled "Interferometric Apparatus For Measuring

Motions Of A Stage Relative to Fixed Reflectors" issued Mar. 1998 by Carl A. Zanoni and U.S. Patent No. 5,757,160 entitled "Moving Interferometer Wafer Stage" issued May 1998 by Justin Kreuzer, the contents of both patent applications incorporated herein by reference.

The methods and apparatus described hereinabove may also be used to characterize *in situ* the figure of a bar mirror located off a wafer stage with a dynamic interferometer used as the interferometer located on the wafer stage. Accordingly, for each of the foregoing embodiments relating to characterizing the figure(s) of bar mirror(s) with measuring surface(s) orientated orthogonal to the plane of a wafer on the wafer stage, there corresponds a set of embodiments with the bar mirror(s) located off the wafer stage fixed to a reference frame of a lithography tool and one or more dynamic interferometers located on the wafer stage. An example of such an embodiment may be seen in Fig. 6 to which reference is now made.

Fig. 6 is a diagrammatic perspective view of an interferometric apparatus **602** employing three on-stage, orthogonally arranged dynamic interferometers or interferometer subsystems by which the shapes of off-stage orthogonally mounted, thin, elongated object mirrors and an on-stage mounted, thin, elongated mirror may be characterized in situ along multiple datum lines (preferably in the x-z, x-y, and y-z planes) associated with each mirror as a translation stage **616** is translated along three orthogonal directions, x, y, and z. As will be appreciated, each interferometer subsystem in combination with an associated mirror or mirrors is an interferometer used principally for measuring the displacement of the translation stage **616** so that a wafer **604** held in position on stage **616** by a wafer holder **603** can be precisely positioned in an exposing beam **606** generated by a well-known exposure unit **601** that is mounted with a reference frame **600** (partially shown). The interferometer subsystems are preferably single beam, plane mirror interferometers, although this is not essential to the operation of the invention.

Referring now to **Fig. 6,** it can be seen that system **602** comprises translation stage **616** atop of which is fixedly mounted an interferometer subsystem **610** and an interferometer subsystem **620**. Plane mirrors **650** and **670** are fixedly mounted to reference frame **600**. Plane mirror **650** has a reflecting surface **661** oriented substantially in the x-z plane and elongated substantially in the x-direction. Plane mirror **670** has a reflecting surface **671** oriented substantially in the y-z plane and elongated substantially in the y-direction.

A mirror **680** is fixedly attached to the top of translation stage **616** and also has a top reflecting surface **682** oriented substantially in the x-y plane and elongated substantially in the y-direction.

Fixedly mounted in reference frame **600** (again partially shown) is an elongated plane mirror **690** having a lower reflective surface facing downwardly, towards stage **616**. Fixedly mounted with respect to a portion of stage **616** making translations substantially in only the x direction is a single beam interferometer **631** that is adapted to measure the vertical separation or altitude between mirror surface **682** and the underside of mirror **690**.

Single beam interferometer **610,** having output and return beam components in beam **612,** measures displacement substantially in the x direction and pitch and yaw substantially about the y and z axes, respectively, as before. Single beam interferometer **620,** having output and return beam components in beam **622,** measures displacement substantially in the y and pitch and yaw substantially about the x and z axes, respectively, also as before.

At any altitude the x and y profiles of mirrors **650** and **670** may be measured using the procedures previously described. In addition to this, however, this embodiment permits the x and y shapes of mirrors **650** and **670** to also be measured at different altitudes and as a function of altitude. For example, the x and y shapes may be determined at one altitude of stage **616** and then at another that may be vertically displaced, say 4 to 5 mm, above or below the first. To do this, angular changes in stage **616** introduced by motion in the z-direction must be taken into account for optimal precision.

Interferometer subsystem **631** is adapted in a manner to be described to be sensitive to changes in orientation of the stage **616** by virtue of it being a single beam interferometer, which makes a single pass to the undersurface of **690** and to surface **682**, and is otherwise configured to measure pitch and yaw for beam **633** relative to pitch and yaw for beam **634**. Therefore, if stage **616** rotates about the x or y axis, during a translation in the z direction interferometer **631** corrects for that. With that information for movement in the z direction, rotation of the stage **616** can be determined with motion in z compensated for such that surfaces **671** and **661** can be mapped in the in z-direction as well as y and x directions. A source/detector **630** feeds interferometer subsystem **631** in the manner described in connection with the apparatus of **Figs. 4a** and **4b** which is analogous.

It will also be evident to those skilled in the art that the shape of surface **682** and the underside of mirror **690** can also be obtained in the process of determining the shapes of surfaces **661** and **671**.

From the foregoing, it will be appreciated that thin, elongated mirrors for use in photolithographic applications and equipment may be characterized in situ through the use of interferometer subsystems associated with the mirrors with relative motion introduced by means of controlled motion of a translation stage operating in a mirror characterization mode. The relative motion may be the result of the mounting of the interferometer subsystems on the translation stage and certain of the thin, elongated mirrors mounted off the stage, fixedly mounted to a reference frame, or vice versa. Once the mirrors have been characterized, error correction signals may be used when the apparatus is operated in a measurement mode to precisely position a wafer with respect to the reference frame and in turn with respect to the mask used to expose the wafer.

The feed of a laser beam to the on-stage dynamic interferometers of Fig. 6 may be as described via source/detector 630 or by optical fibers as described by Zanoni, *op. cit.*, or by free space transport as described for example by Kreuzer, *op. cit.*, or some combination thereof.

Based on the teachings and embodiments described hereinabove, other variatins of the invention will be apparent to those skilled in the relevant art and such variations are intended to be within the scope of the claimed invention.